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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES): Woods Hole Oceanographic Institution, Woods Hole, MA. 02543

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13. ABSTRACT (Maximum 200 words)

Results from this program include the following:
-- (1) Tracking of surface activities of sperm whales using HF radio.
-- (2) Quantification of surface and diving activities showing diurnal diving patterns.
-- (3) Tests of towed array for tracking of tag and whale sounds.
-- (4) Design of tracking routines using display of whale tracks from tag localization data in combination with ship tracks.
-- (5) Development of techniques for handling and towing low frequency sound playback transducer independent of ship maneuvering and weather.
-- (6) Assessment of reactions by sperm whales to low frequency signals.
-- (7) Development of a combination HF radio and acoustic transponder tag.
-- (8) Fabrication of an ARGOS satellite tag for whales utilizing the well tested WHOI system for tag delivery and attachment.

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30 June 1994

Dear Eric,

This is a final report of the research accomplishments resulting from ONR Grant N00014-92-J-1816, entitled "Tag Development and Response of Sperm Whales to Low frequencies". Attached are a list of publications and reports from this program, figure captions, and seven figures. We are pleased with results from this work.

The focus of this ONR program was (1) development of tag systems for objective measurement of sperm whale activities and (2) for assessment of changes in whale activities that might be indicative of responses to low frequency noise.

Our accomplishments include the results of series of experiments in the laboratory and during a cruise with sperm whales (8-28 April 1993, southeast Caribbean). These included assessments of a variety of shipboard tracking systems put together for this cruise (floating hydrophone array, towed array, towed 360° sonar, radio ADF), development of techniques to handle low frequency acoustic playback equipment underway, preliminary playbacks of low frequency sound to whales, and the development of two new whale tags.

Results include the following:
-- (1) Assessment of detailed tracking of the surface activities of long diving sperm whales using HF radio.
-- (2) Quantification of the durations of surface and submergence activities from the accurate HF radio tag signals, for refinement of previous dive data and programming of satellite tag transmissions.
-- (3) Tests of the potential for continuous tracking of tag and whale sounds with towed hydrophone array systems.
-- (4) Design of monitoring routines to allow rapid calculation and display of whale tracks from tag localization data in combination with ship tracks.
-- (5) Development of techniques for handling and towing the low frequency sound playback transducer independent of ship maneuvering and ocean conditions.

-- (6) Provision of preliminary assessments of the nature of any reactions by sperm whales to playback of low frequency signals.
-- (7) Development of a combination HF radio and sonar transponder tag.
-- (8) Fabrication of an ARGOS satellite tag for whales utilizing the well tested WHOI system for tag delivery and attachment.

(1) Assess radio tracking of long diving sperm whales to supplement the short ranges inherent in acoustic tracking -- The HF radio tag proved effective in following the details of sperm whale surface activities over the relatively long distances covered during sperm whale dives. Our previous tracking of sperm whale underwater activity with acoustic sonar transponder tags demonstrated that their underwater movements could be followed in detail, but tracking was short range and consistently interrupted at night by biological scatterers (Figure 1). The radio tracking demonstrated that the HF tag could effectively supplement the acoustic tracks, providing reliable tracking signals for each whale surfacing, well beyond the distances travelled by sperm whales during dives.

(2) Follow details of whale surface activities -- The HF radio tag provided signals at each exposure of the tag antenna above water, accurately detailing the whale's surface activity. Tracking was usually at distances of 1 to 5 km so the ship track provided an approximation of the whale's surface positions (Figure 2). These data indicated diel variation in relative submergence and surface times. During daylight, shorter dives and more frequent surface activities were interspersed with longer dives, while at night there were only longer dives of 40 min or more (Figure 3). Surfacings between the dives averaged 8 min, regardless of dive duration.

Our previous data on dive and surface durations from acoustic tags (as in Figure 1) were inherently inaccurate because of inconsistent acoustic signals when the whale was near the surface. In contrast, the HF radio provided accurate data for each surfacing at ranges to 30 km with good data on blow intervals and other activities. The timing of surface activities also were important for scheduling of signal transmissions from our satellite tags for sperm whales.

(3) Develop tracking by towed hydrophone arrays -- Hydrophones towed from the ship during much of the last cruise tested the potential for simultaneous tracking of both tag and whale sounds while the ship is underway. We found that such continuous towing required well strengthened elements in array

strings (a number of elements failed). From our quiet research ship (ABEL-J), the towed array provided acceptable listening conditions above about 900 Hz while monitoring the sounds produced both by sperm whales and our tags. Signals received by the towed array were compared with those from our sensitive, floating hydrophone array, used normally for broad-bandwidth listening and localization while the ship is stopped. Multi-channel signal processing techniques for acoustic tracking were tested for use in the development of on-line tracking software. Techniques were devised for handling and towing two 300-m array strings without interference with other towed transducers (seven cables in the water). Towed hydrophones allowed us to keep account of the number of whales that were audible -- as in the 1991 tracking, the large male sperm whales that were tagged appeared to move among different groups of smaller whales, so that the numbers of audible whales varied in different parts of the track.

(4) Design monitoring displays for tracking -- Dynamic monitoring displays for the ship track and the acoustic and radio tracking data were developed for maintaining contact with tagged whales during tracking. The continuing display of ship and whale tracks demonstrated the advantages of on-line graphic displays for maintaining specific tracking distances without bringing the ship so close as to be disturbing (Figure 4). Navigational data (GPS, heading, speed, distance log, etc.) were continuously logged by computer, along with the tag monitoring data, such as sonar display (direction, distance, depth range), tag telemetry, and radio ADF bearing. These data were used to follow the underwater movements of tagged whales in three dimensions (Figure 5). This made tracking easier, and it provided means for immediate assessment of horizontal and vertical components of a whale's diving behavior. Monitoring of both horizontal and vertical components of whale activity are important for assessment of movement related responses. Field tests of the acoustic and radio systems were important for the design of algorithms for on-line tracking needed to follow any changes in whale movements indicative of response to sound.

(5) Develop techniques for lc [illegible] equency playback during tracking -- A primary concern for [illegible] cruise was the design of a sea-kindly technique for transmitt[illegible] low frequency sounds while the ship was underway during tracking of tagged whales. A Sanders Model-30 transducer was selected as appropriate for the frequencies and levels needed for transmission of sound during playbacks. Signals at levels up to 190 dB could be transmitted, commensurate with the loudest sperm whale sounds, providing received signal levels of 120 dB or more at appropriate tracking distances from whales. The transducer and its towing fish with

cables weighed more than 300 lbs., and required robust ways for handling and towing. The towing depth of approximately 50 m was selected to provide optimum distribution of sound propagation vertically and horizontally. Both high seas and ship maneuverability contributed to potential handling difficulties, but the transducer towing techniques that we evolved allowed calibrated, controlled, low-frequency sound transmissions to sperm whales as desired.

(6) Preliminary tests of playbacks to sperm whales -- Tests of low frequency sound playback to sperm whales elicited a variety of responses, indicating the reactions to noise that is likely for this species. A 150-sec sequence of the playback signal (860 Hz, 1/3 octave, random-phase M-code, 174 dB) was transmitted when a pair of whales were visible at the surface at a range of 400 m. The received signal level was estimated at 120 dB. With the onset of the playback signal, the whales startled and dove quickly. At their next surfacing, their course was reversed, and they were moving away. Over the next half-hour, these whales swam silently near the surface (short submergences and frequent surfacings), and they continued to move away from the area (Figure 6). Other sperm whales near the surface at distances of approximately 1 km stopped clicking for a period in apparent response to the playback signal, estimated to have been received at a level of about 112 dB (Figure 7). With the onset of a 12-sec playback signal (barely visible in Figure 10 because of high pass filtering at 900 Hz), the whale stopped clicking and remaining silent for 1 min and 25 sec. Whales at greater distances quieted for shorter periods to this playback signal, and whales that were even farther away did not appear to respond at all.

These preliminary tests of low frequency sound playbacks to sperm whales agree with our previous experiences with these whales. The consistent whale response to novel and relatively low level sounds has been silence for a short period. To higher level sounds at received levels at or above about 120 dB, sperm whales reacted by quieting for longer periods, changing activity, and moving away. These preliminary playback experiments confirmed the kinds of responses that can be expected to low frequency sound playbacks during tracking of tagged whales.

(7) Development of a combined HF radio and acoustic transponder tag for following sperm whales both at the surface and underwater -- The development of the combination tag incorporating both our HF radio and acoustic transponder systems provides an important tracking tool for these long diving whales. This combined tag has been completed. We were unable

to use it during the cruise because the sequence of funding did not provide enough time for the fabrication and testing (pressure and ballistics) and last minute refurbishing needed for the field units -- we had insufficient time to deal with antenna coatings that failed final pressure tests. This combination tag is planned for the next phase of this work (ONR N00014-94-1-0812). These tags provide unequivocal identification of the individual whale being observed, direct measures of normal activity, and direct observation of any changes in whale behaviors, both underwater and at the surface.

We hold U.S. Marine Mammal Permit #765 for tagging and tracking of whales, and for these sperm whale cruises, we maintain direct participation with the Fisheries Office of Dominica. In addition, we obtain permission from the French Government to track in waters of Guadeloupe and Martinique. Our HF radio frequency at 30.84 MHz is licensed by the U.S. FCC, to make sure that we have as clear a radio channel as possible.

(8) Development of a satellite tag for whales -- The development of a satellite tag that utilizes the identical delivery and attachment system as for all of the other WHOI whale tags was also included in the tag development package for this past effort. This tag also has come to fruition. The satellite version of the WHOI whale tag was field tested during a cruise in the Southeast Caribbean in May 1994 (other support). Whales were not tagged as planned during the latter part of that cruise because we did not locate any suitable for tagging during that period. The next use of these satellite tags is planned for August 1994 during a cruise sponsored by Iceland's Marine Research Institute in which fin and sei whales will be tagged. Tracking by Service ARGOS will provide the data needed to evaluate performance and period of retention, as well as the whales' local movements and migrations.

Sincerely,

William A. Watkins

PUBLICATIONS AND REPORTS
-- work related to this program.

Tag Development and
Response of sperm whales to Low Frequency Noise

Watkins, William A., et al. In prep. Satellite tag for open ocean whales.

Watkins, William A., et al. In prep. Surface and underwater tracking with one whale tag.

Watkins, William A., et al. In prep. Surfacing and dive patterns of sperm whales from tag tracking data.

Watkins, William A., et al. In prep. Response of sperm whales to preliminary playbacks of low frequency sound.

Watkins, William A. 1993. Cruise report, ONR code 1123B, B. J. Zahuranec, 4 May 1993, with preliminary cruise data on sperm whale tracking, surfacing, and responses to low frequency sound playbacks, 5 pp, enclosures.

Watkins, William A. 1993. Report of sperm whale tagging and tracking with HF radio,and of whale reactions to sound playback sequences. Report (12 May, 1993) for Marine Mammal Permit #765. Report to U.S. Department of Commerce, National Marine Fisheries Service, Washington, D.C., 8 pp.

Watkins, W. 1993: Sperm whale tracking underwater and at the surface. ABSTRACTS, Tenth Biennial Conference on the Biology of Marine Mammals, 11-15 November 1993, Galveston, TX. The Society for Marine Mammalogy, p. 111.

Moore, Karen E., William A. Watkins, and Peter Tyack. 1993. Pattern similarity in shared codas from sperm whales (Physeter catodon). Marine Mammal Science 9:1-9.

Watkins, W. A., et al. 1993. Sperm whales tagged with transponders and tracked underwater by sonar. Marine Mammal Science 9:55-67.

Watkins, W. A., et al. 1994. Fishing and Acoustic Behavior of Fraser's Dolphin (gLagenodelphis hosei) near Dominica, Southeast Caribbean. Caribbean Journal of Science 30:76-82.

FIGURES AND CAPTIONS

Figure 1
Sperm whale dives from sonar transponder tag data -- Sperm whale dives tracked by sonar transponder were consistently obscured in the middle of the night by biological sound scatterers.

Figure 2
Ship track with positions of radio signals during tracking -- Signals from the HF radio tag on a sperm whale are plotted relative to the ship track. The ship track provides an approximation of the whale movements although tracking was maintained at distances of 1 to 5 km to keep from disturbing the whale. After tracking was terminated at 08:20 off Martinique on 25 April 1993, tag signals continued to be monitored as the ship moved toward Dominica, and signals were received at distances of more than 30 km. Tag signals were not automatically related to the ship navigation during the first 6 hours after tagging at 11:40 on 23 April. Throughout the track, correlations could be made with underwater whale sounds from the different groups of sperm whales encountered by the tagged whale (a large male).

Figure 3
Surface and dive times from radio tag data -- The radio tag signals during tracking provided good measures of surface and dive times for the sperm whale. The plot of these data indicate a strong diurnal pattern to the whale activities.

Figure 4
Ship and two-dimensional whale tracks during a dive -- Movements of the ship and a tagged whale during a dive are plotted in two dimensions (starting at the top) to show the ability to track while maintaining a discreet distance from the submerged whale. These whale tracks also are related directly to bathymetry during tracking, and the plot shows bottom topography measured during tracking, related to stored data from our previous surveys in the area.

Figure 5
Ship and three-dimensional whale tracks of the same dive -- Movements in three dimensions are plotted for the ship and the whale for the same dive (as in Figure 4). Depth data is from the tag telemetry, and horizontal underwater vectors are from the sonar tracking of the acoustic transponder tag. The track orientation is rotated here to start at upper right. Dots on the whale dive track are at 30 sec intervals to indicate relative speeds.

Figure 6

Sperm whale responses to a 150-sec playback at 400 m -- The playback (rectangle) on the ship track (line with travel direction arrows) began when whales 1 & 2 were at the surface and had moved to "B". These whales startled, dove quickly, swam silently underwater, surfaced at "C" 30-sec after the playback, reversed course from their previous direction of movement, and then swam silently near the surface as they moved through "D" and "E". The maximum received level by these whales of the 860 Hz M-code playback signal was calculated to be about 120 dB. The other five whales at greater distances appeared to ignore the playback except that they all reversed their direction of movement, and swam slowly away from the playback position. The ship followed at a distance, maneuvered to better observe the whales, and then turned away.

Figure 7

A sperm whale quiets in response to a 12-sec playback at 1 km. -- Two sperm whales seen diving after respiration at approximately 1 km interrupted their clicking for 1 min and 25 sec in response to a 12-sec playback. The received level of the 860 Hz M-code signal by these whales was calculated to be about 112 dB. The figure shows the click sounds as a waveform display at the top and as a spectrogram at the bottom (vertical frequency range of 40 kHz and horizontal time span of 2 min 43 sec). More distant whales continued clicking.

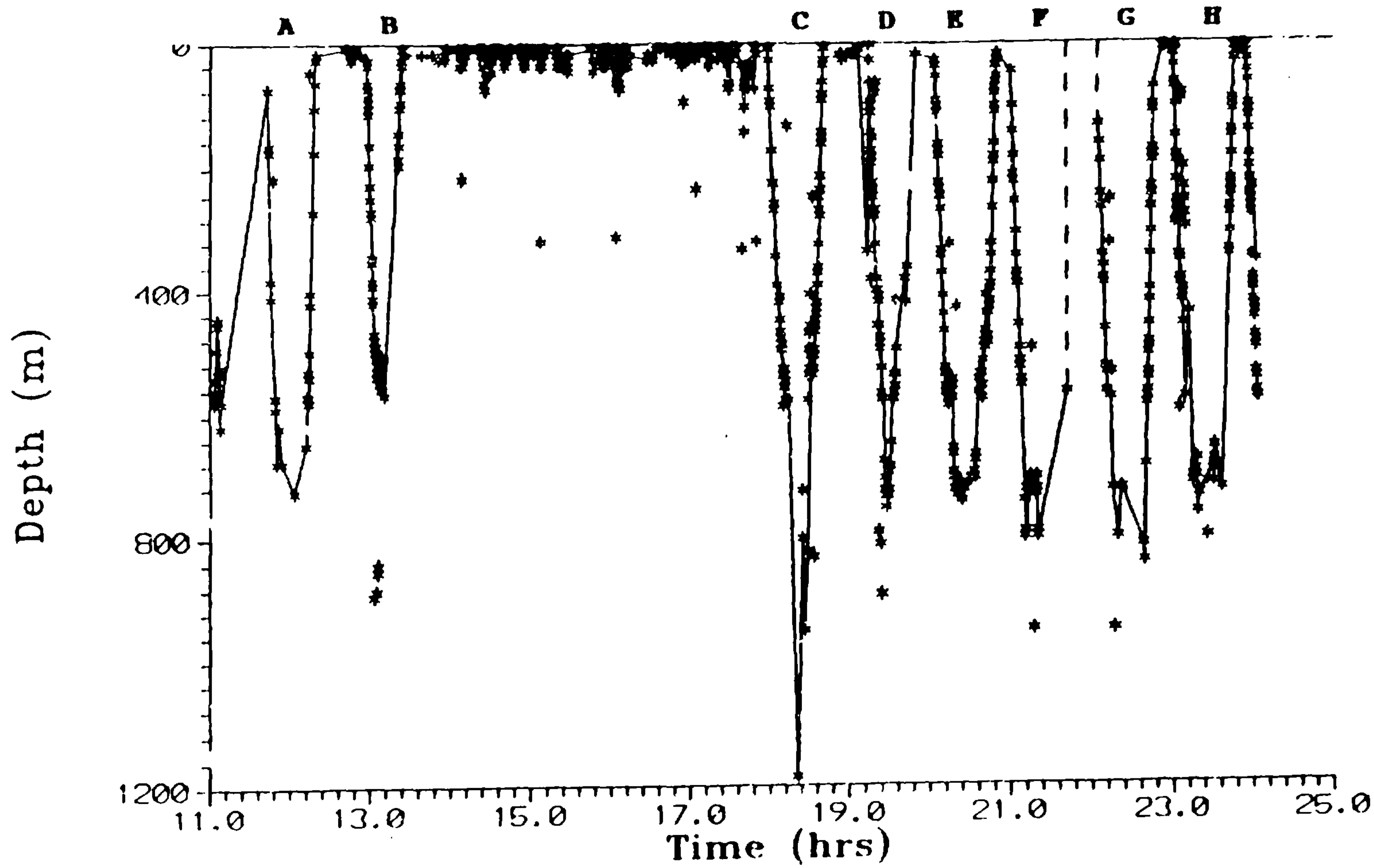
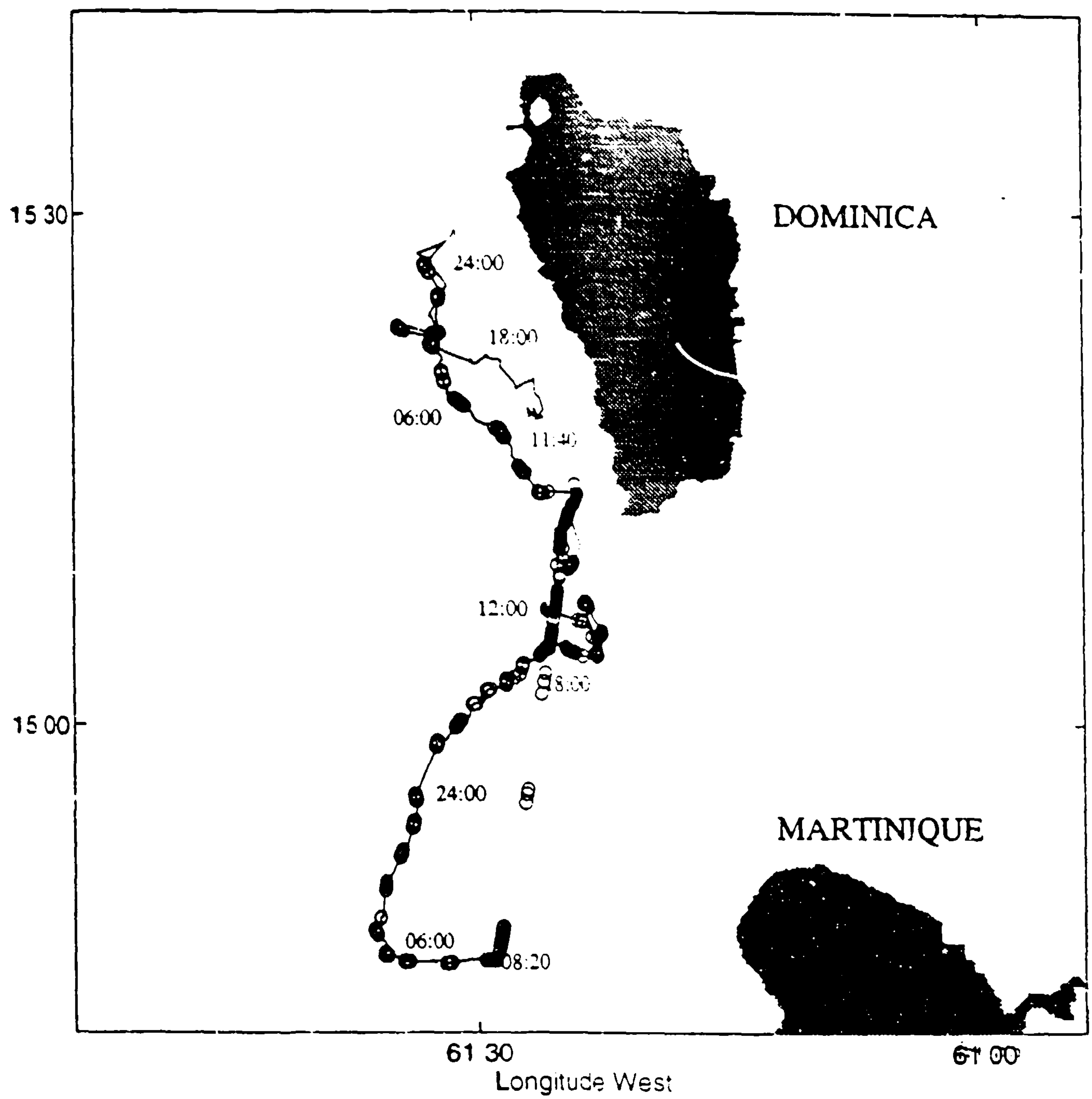
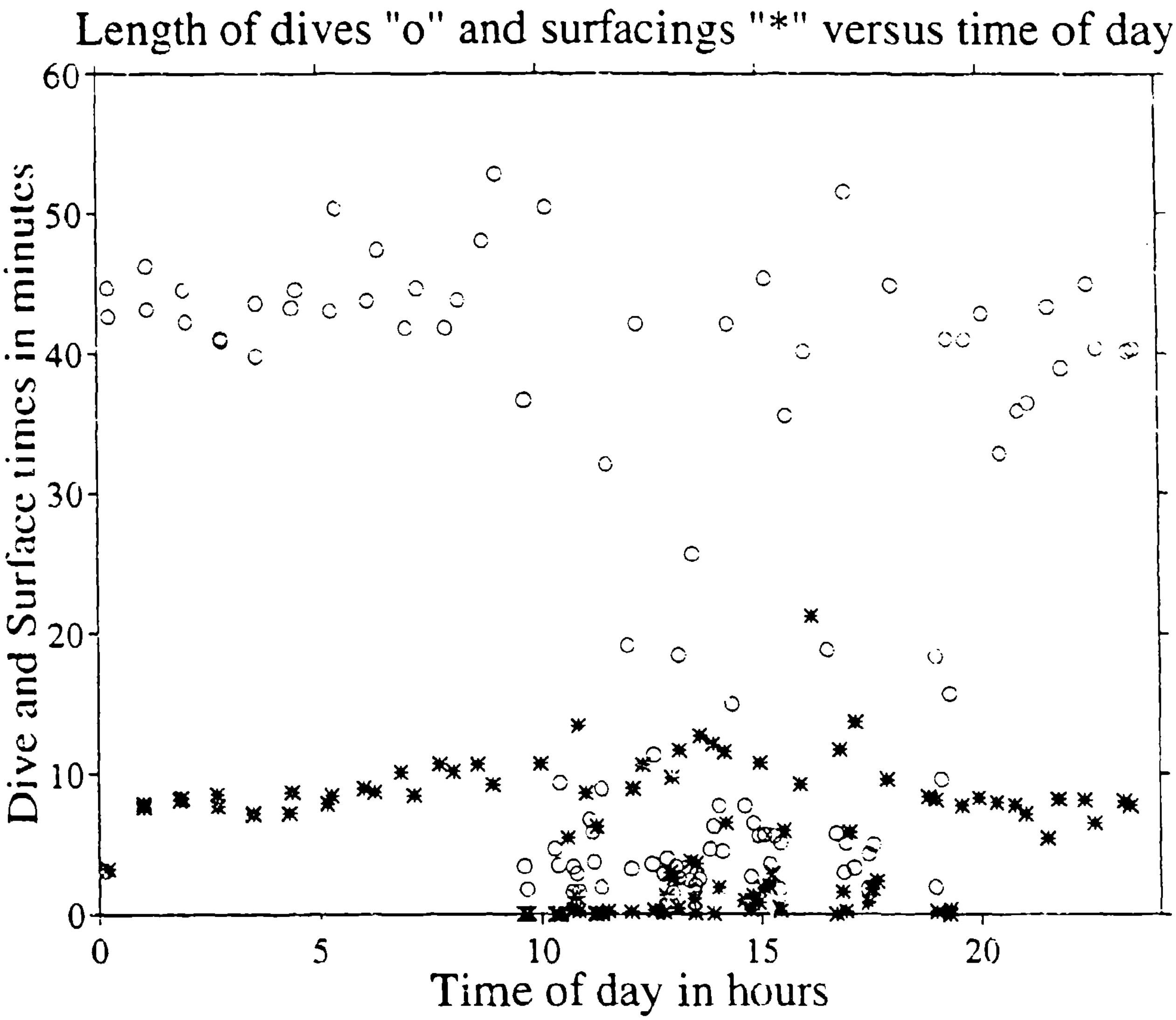

A
B
C
D
E
F
G
H
0
400
800
1200
11.0
13.0
15.0
17.0
19.0
21.0
23.0
25.0
Depth (m)
Time (hrs)

Figure 1



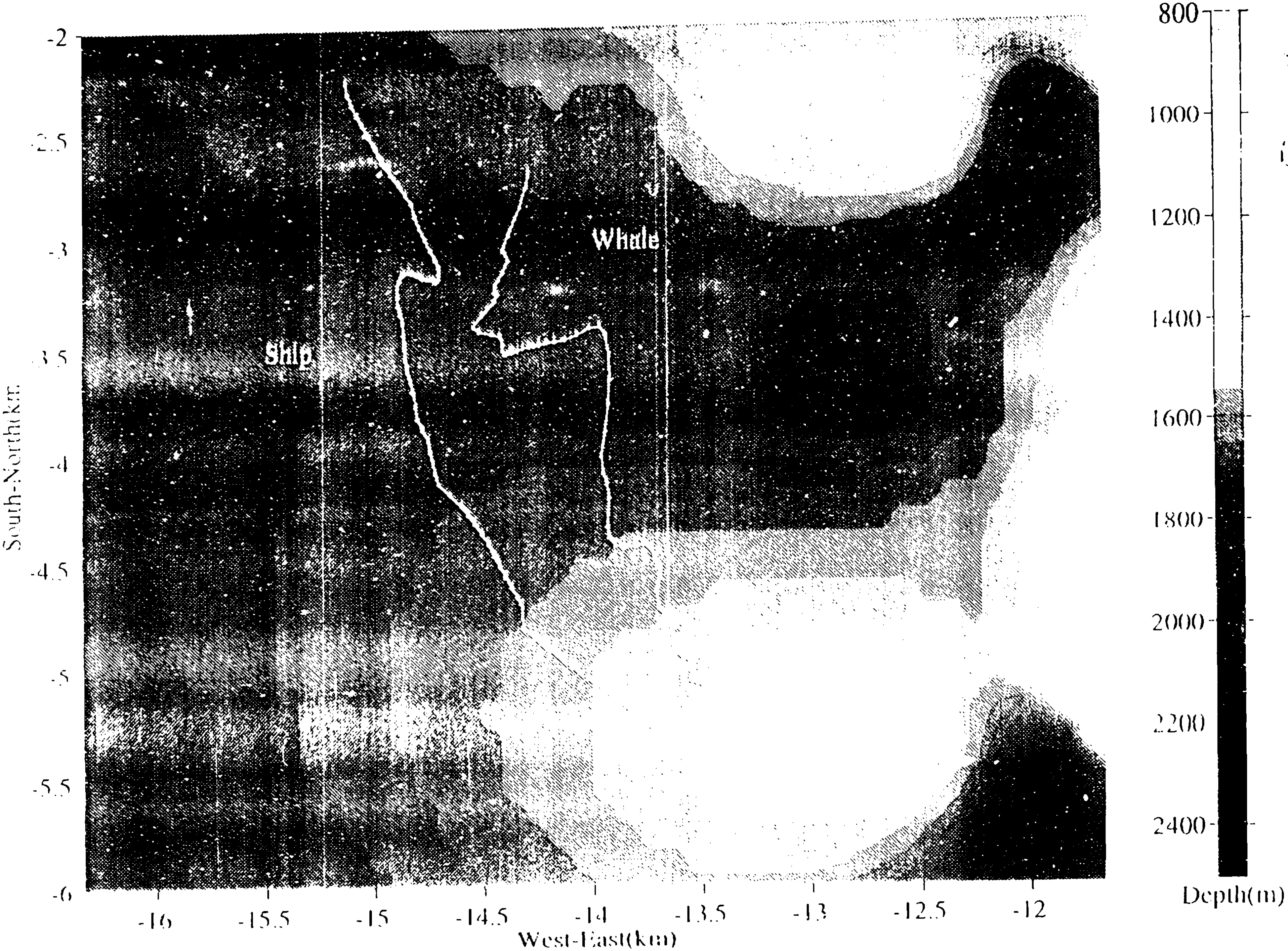
15 30
15 00
DOMINICA
MARTINIQUE
24:00
18:00
06:00
11:40
12:00
18:00
24:00
06:00
08:20
61 30
61 00
Longitude West

Figure 2



Length of dives "o" and surfacings "*" versus time of day
Dive and Surface times in minutes
Time of day in hours
0
10
20
30
40
50
60
0
5
10
15
20

Figure 3



-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6
South-North(km)
Whale
Ship
-16
-15.5
-15
-14.5
-14
-13.5
-13
-12.5
-12
West-East(km)
800
1000
1200
1400
1600
1800
2000
2200
2400
Depth(m)

Figure H

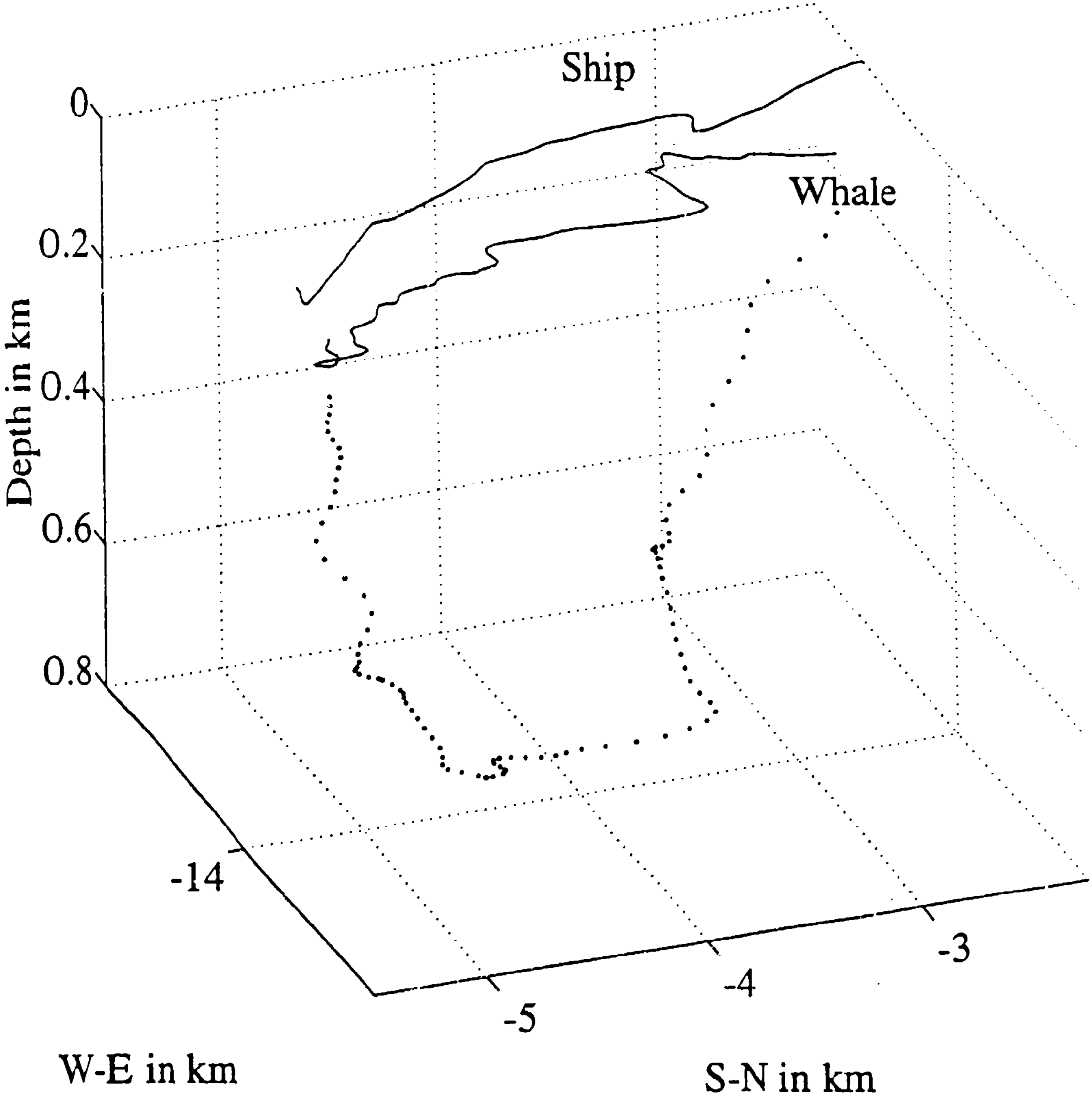


Figure 5

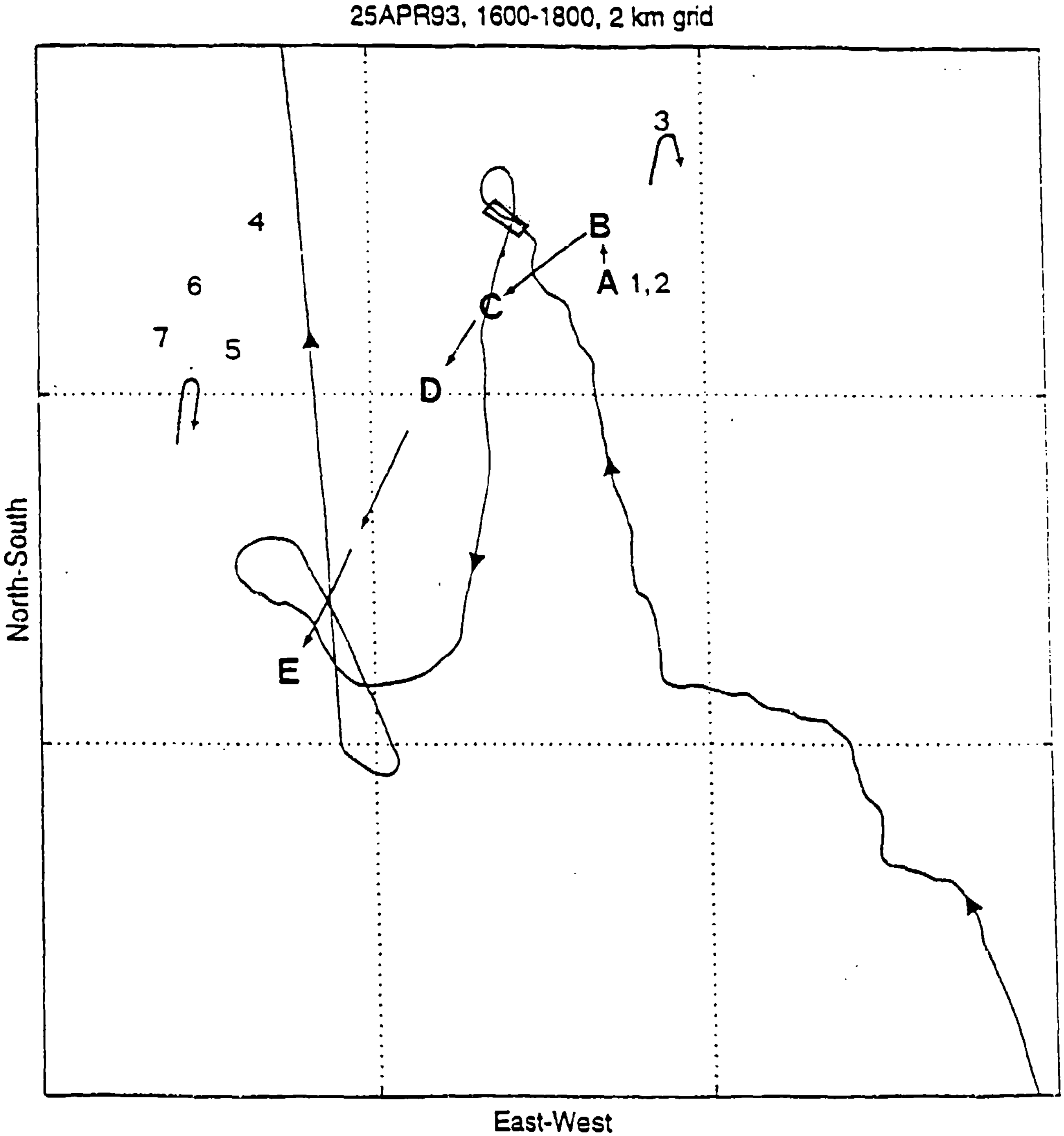
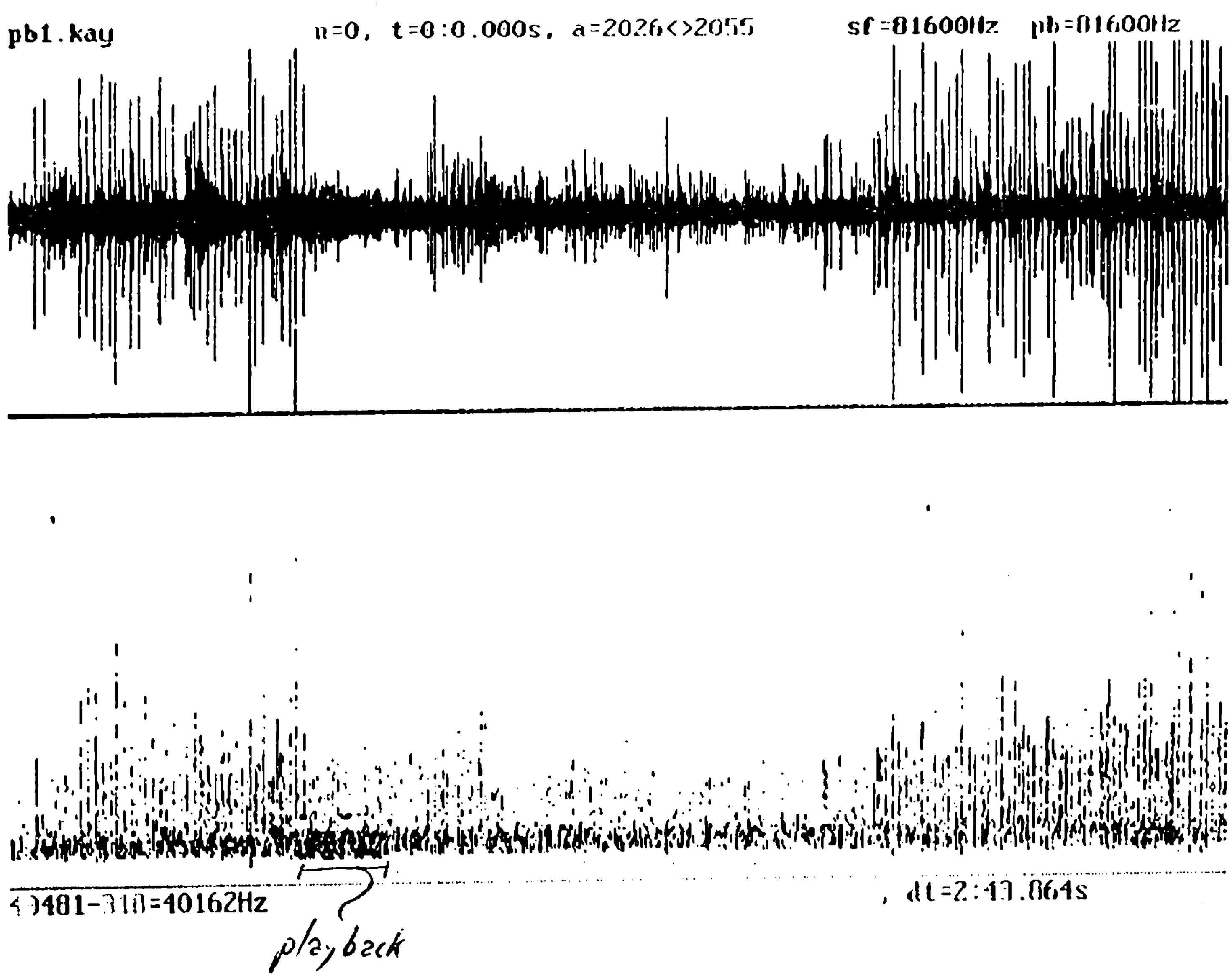

25APR93, 1600-1800, 2 km grid
3
4
B
A
1,2
6
C
7
5
D
E
North-South
East-West

Figure 6


pb1.kay
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sf=81600Hz
pb=81600Hz
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playback

Figure 7